A Terahertz Wave Parametric Amplifier With 55dB Gain

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Abstract—This work demonstrates THz wave amplification in a non-linear MgO:LiNbO₃ crystal using a parametric process. The amplifier has gain in excess of 55dB. This system has potential applications in non-destructive sensing and imaging of a wide variety of materials.

I. INTRODUCTION

The development of optoelectronics and laser technology has enabled the efficient generation of broadband terahertz (THz) wave. The applications of this wave have expanded into diverse fields and practical applications, such as illicit drug detection, non-destructive inspection of wide variety of materials, scientific applications such as THz non-linear spectroscopy and so on [1]. However, it is still necessary to develop novel THz sources or to improve the performance of existing sources to develop broadband and high-power THz wave generation that could allow us to expand THz applications further.

In recent years, various methods of achieving high-power THz waves have been reported. Examples include THz wave parametric generation [2], optical rectification of femtosecond pulses in organic and inorganic crystals [3], and quantum cascade lasers [4]. All of these sources have been applied in a wide variety of research fields, such as THz imaging and THz spectroscopy. Despite their better performance in such applications, it is still difficult to measure samples with strong absorption in transmission mode. In order to overcome such problems, it is necessary to either increase the power of the THz wave or improve the sensitivity of the THz detectors.

In order to address such problems, recently, we demonstrated the high dynamic range THz-wave spectrometer using parametric processes in lithium Niobate crystal [5]. This system has the dynamic range of more than 7 orders, and the intensity spectra extended from 1.1 – 2.5 THz. As another approach, we demonstrated the amplification of THz wave via non-linear optical processes in Lithium Niobate crystal [6]. This method allows us to amplify the THz wave transmitted through the samples so that conventional THz sensors, such as pyroelectric detectors, can easily detect the THz wave. Moreover, the amplification of THz wave enables us to compensate the attenuation loss due to strongly absorbing samples. In our previous work, the amplifier crystal was pumped using a pump beam after it was transmitted through the emitter crystal. Here, we separately pumped the emitter and amplifier crystals, which enabled us to significantly improve the gain of the system.

II. RESULTS

Figure 1 shows the experimental setup, which consists of two major parts: a THz wave emitter and a THz wave amplifier. As a THz wave source, we used an injection-seeded THz parametric generator (is-TPG) [7][8]. The pump source was diode-end-pumped, single-mode, linearly polarized microchip Nd³⁺:YAG laser, which was passively Q-switched using a [110]-cut Cr⁴⁺:YAG saturable absorber [9]. The output wavelength was 1064 nm, the pulse width was 500 ps, the pulse energy was 0.7 mJ/pulse, and the repetition rate was 100 Hz. The output of the laser was amplified using two optical amplifiers in a double-path configuration. We obtained a pump energy of 12 mJ/pulse. We used a continuous-wave (CW) tunable external cavity diode laser (ECDL) with an average power of 450 mW as an injection seed for the idler beam. The seed beam passed through an achromatic phase-matching optical setup designed to compensate for the dispersion caused by the LiNbO₃ crystal. When the pump beam and seed beam were injected into the nonlinear crystal at an angle of incidence such that the non-collinear phase-matching condition was met, a coherent, single-frequency, widely tunable THz-wave was generated. Note that the THz-wave generated within the nonlinear crystal will undergo total internal reflection due to the large refractive index mismatch between the LiNbO₃ crystal and the air. Therefore, to avoid these reflection losses, an undoped Si prism coupler was placed on the y-surface of the nonlinear crystal.

Figure 1. Experimental setup used for THz wave amplification
Similarly, to avoid reflection losses, the Si prism coupler was also used at the amplifier crystal.

In our previous work [6], the amplifier crystal was pumped by a laser beam after it was transmitted through the emitter crystal. However, the laser beam transmitted through the emitter crystal had poor beam quality (such as poor spatial beam profile and distorted pulse). Thus, in this work, we changed the experimental setup to avoid those problems. Here, the pump beam was divided by a polarizing beam splitter (PBS): one portion was used to pump a MgO:LiNbO$_3$ crystal, which produced THz waves based on parametric processes, and the other portion was used to pump another crystal where the THz wave was amplified. Here, the pumping beam and THz-wave to be amplified were used to irradiate another MgO:LiNbO$_3$ crystal. In this case, the THz wave acts as a seed beam and due to the interaction between the THz wave and pump beam in a nonlinear crystal, an amplified THz wave is emitted from the crystal.

The THz-wave amplified in the MgO:LiNbO$_3$ crystal was coupled out through a silicon prism. Figure 2 shows the gain plotted as a function of the input THz energy. The gain is calculated as $G = 10 \log_{10}(E_{\text{out}}/E_{\text{in}})$, where $E_{\text{out}}$ and $E_{\text{in}}$ are the THz input and output energy respectively.

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The THz-wave amplified in the MgO:LiNbO$_3$ crystal was coupled out through a silicon prism. Figure 2 shows the gain plotted as a function of the input THz energy. We varied the THz-wave energy from 18 aJ to 220 nJ using THz attenuator, and measured the THz-wave energy using an infrared pyroelectric detector. Here, we succeeded in amplifying a THz wave with energies of 18 aJ to 2 nJ, which gives a gain of 55 dB.

In this work, we demonstrated THz wave amplification in non-linear MgO:LiNbO$_3$ crystal using a parametric process. Our system shows a good potential to amplify the weak THz signal with the energy as small as few aJ/pulse. The gain of this system is 55 dB, which is higher in comparison to our previous work. The improvement of the gain is mainly due to the separate pumping of emitter and amplifier crystals. We expect that our THz amplification scheme find an application in a wide range of applications such as THz spectroscopy or THz imaging.

**III. SUMMARY**

In this work, we demonstrated THz wave amplification in non-linear MgO:LiNbO$_3$ crystal using a parametric process. Our system shows a good potential to amplify the weak THz signal with the energy as small as few aJ/pulse. The gain of this system is 55 dB, which is higher in comparison to our previous work. The improvement of the gain is mainly due to the separate pumping of emitter and amplifier crystals. We expect that our THz amplification scheme find an application in a wide range of applications such as THz spectroscopy or THz imaging.

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**REFERENCES**


